Assessing the Impact of Mission Requirements, Vehicle Attributes, Technologies and Uncertainty in Rotorcraft System Design

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ABSTRACT*

This research provides a probabilistic design environment for the propagation of design uncertainty to the system level to assist in making more educated decisions in the early stages of design. This design uncertainty is associated with the key elements that are addressed in system design and which are captured in the appropriate design environment, namely mission requirements, vehicle attributes and technologies. The proposed environments are constructed using a metamodeling technique called Response Surface Methodology (RSM) and provide a model relating system-level responses to the mission requirements, vehicle attributes and technologies. The Mission Space Model is concerned with mission requirements exclusively and provides the ability to model an infinite set of missions. The Unified Tradeoff Environment (UTE) integrates the mission requirements, vehicle attributes and technologies in a single environment while allowing both deterministic and probabilistic analyses. The design environments and design methods proposed in this research are demonstrated for a rotorcraft of current interest, namely the Future Transport Rotorcraft, and probabilistic applications are presented.

INTRODUCTION

Many forces shape the modern design environment from the complexity of modern systems to changes in design philosophy to the emphasis placed on affordability. Perhaps the most difficult place to operate in this environment is at the beginning of the design process (system design stage) where uncertainty infiltrates many aspects of design. Decisions made at this time have significant repercussions on the overall system capability and cost and thus system success. Dieter[1] and Fabrycky & Blanchard[2] maintain that while the early design stages account for a small fraction of the overall system cost, the design decisions made at this time commit a large portion of the system life-cycle cost. It is during this stage of design that design freedom is most open but design knowledge is scarce. Thus, "just at the time when decisions are most critical (and most efficiently and affordably implemented), the state of information about the alternatives is least certain."[3] The research presented in this paper seeks to provide a design environment for making educated decisions in the early phases of complex system design.

To this end, it deals with the key elements in the early design of complex systems. These are identified as mission requirements, vehicle attributes and vehicle technologies and referred to collectively as the information triad. However, this research also acknowledges design uncertainty as another key element in early decision making. In a broad view, uncertainty implies that multiple outcomes or results are possible. In the context of system design, this implies that multiple system responses are possible when variability associated with design information (i.e. mission requirements, vehicle attributes, and technologies) is propagated to the system level. In any design process, which hopes to account for variability or uncertainty, the response or outcome of interest will not be given as a point estimate but will inherently be projected in the form of a probability distribution. This response distribution is the product of propagating design variable uncertainty to the system level.

The notion of accounting for design uncertainty is not a new concept in design theory. Robust and probabilistic design methods deal with uncertainty but usually in the latter design stages. The reliability of a component or part is determined by propagating design uncertainty to the stresses and strains seen by the component over its lifetime. Cost estimating methods often address uncertainty by describing cost elements as probability distributions instead of point estimates and propagating the uncertainty to the total cost of the system. The application of robust or probabilistic design methods at the aerospace system design level to address concerns with mission requirement, vehicle attribute or technology uncertainty is sparse.

One of the first applications is given by Mavris, Bandte and Schrage[4] for the economic uncertainty assessment of a High Speed Civil Transport (HSCT). In this work a fixed configuration, sized for a single mission and with a prescribed technology set, is subject to uncertain economic variables. This treatment of the HSCT is extended in Reference 5 to include vehicle attributes. Vehicle attribute settings are found for an HSCT while considering economic uncertainty. In the work by DeLaurentis[6], the influence of stability and control uncertainty (discipline uncertainty) and economic uncertainty (operational uncertainty) are investigated for their impact on an HSCT. Although he acknowledges the uncertainty associated with mission

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* Presented at the American Helicopter Society 58th Annual Forum, Montreal, Canada, June 11-13, 2002.

requirements and technologies and provides a generic method for their inclusion, they are not explicitly investigated. A different formulation for the HSCT is provided by Chen et. al.[7] to identify robust top-level specifications. In this study uncertainty associated with vehicle attributes and propulsion system attributes (technology) are considered in identifying a robust range for top-level specifications under different design scenarios.

Kirby[8] looks extensively at the infusion of new technologies at the system design stage both from the perspective of technology magnitude and technology readiness. Her examples are again directed at the design of an HSCT and do not include the impact of mission requirements. Uncertainty associated with technology maturity is addressed through a pre-determined probability distribution associated with a Technology Readiness Level. This technique is used for ranking technology combinations and for resource allocation. Other works including the introduction of technology uncertainty are found in Reference 9 for a Short Haul Civil Tiltrotor (SHCT) and Reference 10 for an Uninhabited Combat Air Vehicle (UCAV).

The inclusion of mission requirements in a robust or probabilistic design process is first seen in Reference 11 for an economic assessment of the High Speed Civil Transport. Vehicle attribute settings are determined under economic uncertainty at discrete levels for mission parameters. Mission requirement uncertainty is addressed briefly in Reference 12 through two subsonic mission segment lengths and a climb optimization factor. Vehicle attribute settings are determined under economic and mission requirement uncertainty.

A review of current research connecting system design, the information triad and design uncertainty indicates much of this research concentrates on identifying robust vehicle attributes (based on economic uncertainty). This work provides both deterministic and probabilistic evaluation of their impact on the system as well as the impact uncertainty has on their values. The impact of technologies and technology uncertainty also receives in-depth attention. The impact of technologies on the system is investigated both with and without uncertainty assessment. *However, the treatment of mission requirements in a robust or probabilistic design formulation receives little attention.*

This research proposes a design environment that is able to simultaneously assess the impact of mission requirement, vehicle attribute and technology changes on the system level responses as well as propagate design uncertainty associated with the information triad to the system level. This research does not abandon traditional design methods and tools which have produced extremely capable aircraft over the last half century. It endeavors to enhance these methods by building a design environment compatible with current analysis codes while being amenable to probabilistic techniques. Particular attention is given to the impact of mission requirements individually and in concert with vehicle attributes and technologies since they receive little attention in current research. The two design environments proposed in this research are the Mission Space Model (mission requirements) and the Unified Tradeoff Environment (mission requirements, vehicle attributes and technologies). The design environments and design methods proposed in this research are demonstrated for a rotorcraft of current interest, namely the Future Transport Rotorcraft, and both deterministic and probabilistic applications are presented.

BACKGROUND

One of the most critical aspects in engineering a system is the creation and use of models. In the system design stage, the models are often analysis codes that capture, with some degree of fidelity, the synthesis and sizing of an aerospace vehicle. This process is inherently multidisciplinary and provides challenges with respect to the interaction of various disciplines, the large number of design variables and the multiple objective criteria. A recent development in both multidisciplinary design optimization (MDO) methods as well as probabilistic design methods is the use of metamodels. These metamodels are defined by Kleijnen[13] as “models of models” and they provide a simple, easily manipulated approximation of a more complex model. If properly validated, they provide an efficient method for evaluating an objective function (MDO methods) or an efficient analytical engine for statistical sampling techniques.

In probabilistic design, the outcome sought is either a cumulative distribution function (CDF) or a probability density function (PDF) for each design objective or constraint (i.e. response). These distributions reflect the variability in the response associated with propagating design variable uncertainty (modeled using probability distributions) to the system level. The generation of these distributions entails the linking of deterministic analysis codes with statistical techniques. Fox[14] and Mavris & Bandte[15] list three methods that incorporate such complex computer programs in a probabilistic systems design approach:

1. Link a sophisticated design code directly to a random number generator such as a Monte Carlo Simulation (MCS) to obtain the PDF or CDF.
2. Approximate the sophisticated analysis code with a metamodel and link it with a MCS.
3. Link the sophisticated analysis code with an approximation of the MCS.

Monte Carlo Simulation (MCS) or modeling is a statistical sampling technique used when analytical methods are inappropriate. “Monte Carlo modeling relies on random numbers generated by computer to drive a computer simulation of a system”[16]. The random number generator output is used to sample the distributions of the relevant input variables to provide a new input set for each simulation run. Relevant response values are then collected and as the number of random cases increases, the distribution of response values is analyzed. In this research, Method 2 shown above is employed and the metamodeling technique of choice is the Response Surface Methodology (RSM).

Response Surface Methodology

Response Surface Methodology (RSM)[17] is a method using multiple linear regression techniques along with statistical experimental design methods for the identification and fitting of a response surface model which relates a system response to selected design variables (i.e. mission requirements, vehicle attributes, technology metric dials). RSM is used to mathematically model the proposed design environments in this research.

Generally, the exact deterministic relationships that govern the behavior of the measured responses to the set of design variables is either too complex or unknown. Therefore, an empirical model is constructed which captures the system response as a function of the design variables. The empirical model used in this methodology is assumed to be second order with *k* number of design variables. This second-degree model is assumed to exist and can be expressed in the following form.

$$R = b_o + \sum_{i=1}^{k} b_i k_i + \sum_{i=1}^{k} b_{ii} k_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} k_i k_j + \varepsilon \qquad (1)$$

where:
b_0 = intercept term
b_i = regression coefficients for linear terms
b_{ii} = regression coefficients for pure quadratic terms
b_{ij} = regression coefficients for cross product terms
x_i, x_j = design variables
ε = error

The coefficients of this regression curve (surface) are determined by applying a least squares analysis to the responses generated by a set of simulations identified through a Design of Experiments (DOE).[18] When this model fails to accurately predict the behavior of the complex analysis code, other methods found through independent or dependent variable transformations can be used.

As mentioned above, the coefficients of the RSE are determined utilizing a carefully planned Design of Experiments or simulations. This approach ensures that the resulting RSE will be applicable in a sufficiently large design space without requiring an unrealistic number of simulation runs (or cases) to provide the response data for the regression analysis. The DOE chosen will dictate the number of simulation runs required based on the number of levels considered, the number of interactions modeled and the number of variables prescribed. By employing a fractional factorial DOE the required cases are reduced with higher order effects neglected. Fractional factorial designs neglect third or higher order interactions and, in the case of RSE generation, account for linear and all second order interactions including the quadratic effects (see Equation 1).

TECHNICAL APPRAOCH

As mentioned previously, Response Surface Equations (RSEs) are used in conjunction with Monte Carlo Simulation to propagate design variable uncertainty to system level responses. Previous research, summarized in the Introduction, relies on similar methods. The Concept Space relates system responses to vehicle attributes (includes vehicle geometry and economic variables) while the Technology Space relates them to technology metric dials. Technology metric dials refer to adjustment factors placed on various discipline metrics that allow one to simulate the benefit or penalty associated with applying a technology to the vehicle. Since, the ability to capture mission requirements exclusively in such an environment is not established, the first task is to show the feasibility of creating a "mission" space. This environment is called the Mission Space Model. Once this is established, an environment which simultaneously captures mission requirements, vehicle attributes and technologies is addressed. This integrated environment is constructed using a single Design of Experiments that includes all the desired mission requirements, vehicle attributes and technology metric dials as design variables. The resulting metamodels then capture the system responses as a function of all these variables including all interactions between variables. This environment is called the Unified Tradeoff Environment.

BASELINE VEHICLE

The design environments in this research are built around a helicopter variant of the Future Transport Rotorcraft (FTR). It is a heavy lift rotorcraft envisioned to carry 10 to 20 tons of payload for 300-1000 kilometers at speeds ranging from 175 to 350 knots. A baseline vehicle is established with a mission payload of 40,000 pounds and a mission radius of 270 nautical miles. The baseline mission is shown in Figure 1.

The anchoring point for this configuration is a vehicle similar in size and performance to the CH-53E, thus providing proper trends and scaling laws for this class vehicle. The baseline includes modified 2005 Rotary Wing Vehicle Technology Development Approach (RWV-TDA) goals as well as Integrated High Performance Turbine engine Technology Program (IHPTET, Stage II+) estimates for the engines. The TDA is a structured government/

industry/academia technology approach aimed at addressing technological challenges. It quantifies improvements in the state-of-the-art through measurable goals for system and component level characteristics with respect to established baselines and proposed achievement dates. These assumptions provide a realistic baseline that is not reached by simply scaling the CH-53E-like vehicle to meet FTR requirements. These assumptions are shown in Table 1.

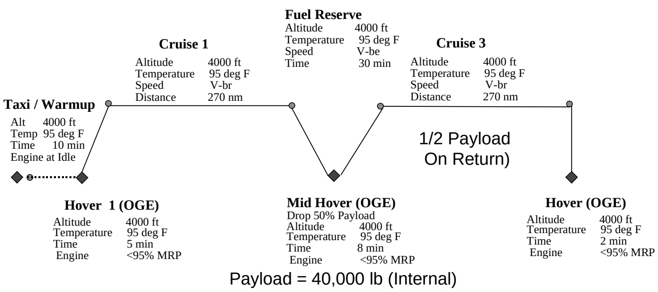

Figure 1: Baseline Mission Profile

Table 1: FTR Baseline Technology Assumptions

Component	Reduction	Component	Reduction
Main Rotor Blades	10%	Fuselage	10%
Main Rotor Hinge	10%	Landing Gear	10%
Main Rotor Hub	10%	Drive Sytstem	13%
Horizontal Tail	10%	Main Rotor Blade Fold	15%
Vertical Tail	10%	Engine Weight	10%
Tail Rotor	10%	Engine SFC	35%

The FTR baseline has seven rotor blades and three engines and its cabin is equivalent to the C-130. All analysis work is conducted using a proprietary industry synthesis and sizing code. Therefore, a description of the FTR helicopter baseline is provided in a normalized fashion when appropriate. The FTR baseline is normalized to the CH-53E to give the reader a general idea of the baseline size and dimensions. This description is given in Table 2.

Table 2: FTR Helicopter Baseline (Normalized)

Vehicle Parameter	Value	Vehicle Parameter	Value
Gross Weight (lbs)	~ 120000	Blade Loading	1.53
Installed Power (SLS, MCP)	2.3	Downloading	1.22
Rotor Radius (feet)	~ 55	Number of Engines	3
Flat Plate Drag Area	1.2	Number of Blades (Main)	7
Fuselage Wetted Area	1.58	Flyaway Cost	2.13
Disk Loading	1.22		

MISSION SPACE MODEL

In order to capture the impact of various discrete missions, as well as the continuous mission space between them, the mission modeling is done at the lowest level possible in the variable hierarchy. Traditionally, mission profiles are constructed from pre-determined mission segments such as takeoff/hover, climb, cruise, descent, loiter, etc. Within each mission segment are the fundamental characteristics which encompass the mission requirements such as the amount of payload to be carried, the distance traveled in cruise, the ambient conditions (altitude, temperature) for each segment and the time spent in each segment (e.g. takeoff/hover, loiter). Therefore, a mission space is created using these fundamental variables as the parameters in the DOE. This DOE is constructed around a baseline vehicle as is the DOEs used to construct the Technology Space (and Concept space). This baseline vehicle acts as a reference point for the ranges used in the DOE and in subsequent use of the metamodels. System level responses are obtained as a function of these parameters allowing the creation of a continuous mission space. Discrete missions are then evaluated by mapping an appropriate vector of mission requirement parameters onto the mission space.

Arbitrarily assigning mission parameters for use in a DOE does not provide the structure needed for this environment. This environment must be built around a primary mission structure in order to provide a reference point for understanding mission parameter effects on the system sizing. This is accomplished by constructing a master mission structure that captures as many of the mission profiles as possible. In the case where numerous mission profiles are prescribed (e.g. the LHX program) then several master mission structures may be needed.

The master mission structure deals mainly with modeling the primary sizing missions for a vehicle. If scores of mission profiles are provided, then missions, which are obviously less stringent are used as secondary missions and flown after sizing the vehicle to determine performance. Most synthesis and sizing codes allow this ability to size a vehicle for a primary mission and then determine performance for alternate missions. When created in this manner, the environment is called the Mission Space Model (MSM). The master mission structure for the Future Transport Rotorcraft is constructed loosely from three missions (Navy, Marine Corps and Army) described as Joint Common Lift (JCL) Heavy Lift-Assault by the Operational Requirements Commonality Assessment (ORCA)[19]. These missions are representative of the types of missions anticipated for the FTR. The master mission structure is illustrated in Figure 2.

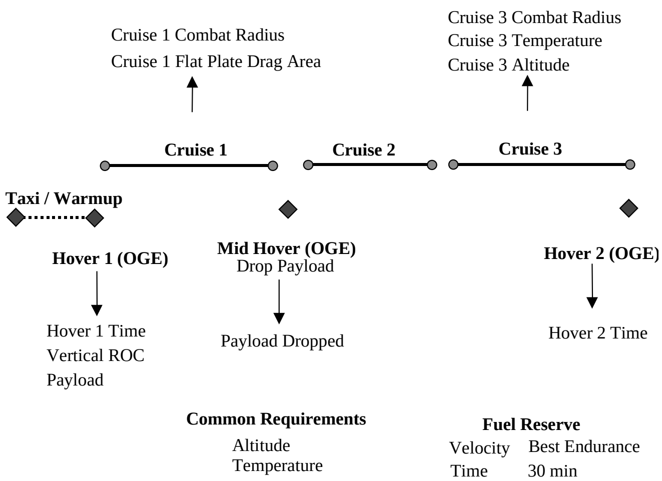

Figure 2: Master Mission Structure

In addition to this structure, the vehicle flies three secondary missions to determine vehicle performance. These missions include a Mid-Hover Assault Mission flown with the same payload and at the same ambient conditions as the sizing mission. The performance measure extracted is the resulting mission range. The Self-Deploy Mission is flown with an initial short takeoff and a cruise at 6000 feet altitude at standard temperature. An assumption is made that 125% payload is converted to fuel and auxiliary fuel system weight. The performance measure tracked for this mission is the resulting range. Finally, the MILVAN Mission requires the lifting of a fully loaded MILVAN along with required cabling (45,000 lbs.) at the ambient conditions associated with the primary mission. The performance measure determined for this mission is the percent of available takeoff power that is required to hover (OGE) with full mission payload.

The Mission Space Model constructed using this structure allows the designer to simulate various ambient conditions and a wide range of payloads including how much payload is dropped. There are three separate cruise range inputs as well the ability to fly the last cruise segment at altitudes up to 8000 feet. The ranges used to create the Mission Space Model for the FTR are given in Table 3 and further give an indication of the wide array of mission profiles that can be mapped. The final input variable, flat plate drag area, is an incremental drag added to the first cruise segment of the primary mission to simulate an external payload. The assumption is made that any payload carried on the return leg is carried internally

The input variables and ranges illustrated in Table 3 are used to construct a Design of Experiments for twelve variables. For this research, a twelve-variable, custom DOE requiring 257 cases is implemented. An automated design environment built around the proprietary analysis code facilitates the running of these 257 cases and the parsing of system level responses. The JMP[20] statistical software is used to build the metamodels (RSEs). A statistical check for the RSEs indicate an excellent fit between the RSEs and the collected response data. The final test of the RSEs is conducted using a random set of simulation runs to determine their predictive capability. The percent difference between predicted responses (using RSEs) and actual responses (using analysis code) for the random cases is used as a measure of the RSE accuracy.

Table 3: Ranges for Mission Space Model

Mission Parameter	Units	Minimum	Maximum
Payload	lbs	30000	50000
Altitude	feet	0	4000
Temperature	F	90	95
Hover 1 Time	min	1	5
Cruise 1 Combat Radius	nm	50	540
Payload Dropped	%	50	100
Cruise 3 Comabt Radius	nm	50	530
Cruis 3 Altitude	feet	0	8000
Cruise 3 Temperature	ISA + C	0	30
Hover 2 Time	min	2	5
Vertical ROC	fpm	0	500
Flat Plate Drag Area	sq feet	0	45

The results of this confirmation test are given in Table 4. This table shows the maximum, mean and standard deviation for the percent difference between the predicted response and the actual response (per analysis code) for the random cases. The mean and standard deviation for each response shows excellent predictive capability with the largest mean percent difference being 3% for Unit Operating Cost/Year. The maximum values for Mid-Hover Range and Unit Operating Cost/Year are high but analyzing the distribution of percent error over the random cases indicates these high values are associated with a few outlying cases.

Table 4: Mission Space Model Predictive Validation

	Percent Difference Actual to Predicted		
Response	Maximum	Mean	Standard Deviation
Gross Weight	6.6	1.2	1.1
Empty weight	6.7	1.2	1.1
HP Installed (SLS,MCP)	9.4	1.7	1.7
Rotor Radius	3.2	0.5	0.4
Aspect Ratio	0.3	0.1	0.1
Self Deploy Range	3.1	0.7	0.5
Mid Hover Range	18.2	1.8	2.1
MILVAN % SHP	9.6	1.9	1.6
RDTE Cost	3.2	0.5	0.5
Unit Acquisition Cost	4.5	0.8	0.7
Unit Operating Cost	16.4	3.0	2.7
Life Cycle Cost	7.2	1.3	1.2

In Figure 3, the Mission Space Model is shown in the form of prediction profiles,[20] that show the relationship between the responses (ordinate) and the mission requirements (abscissa). This screen is an interactive representation of the MSM as captured by the RSEs.

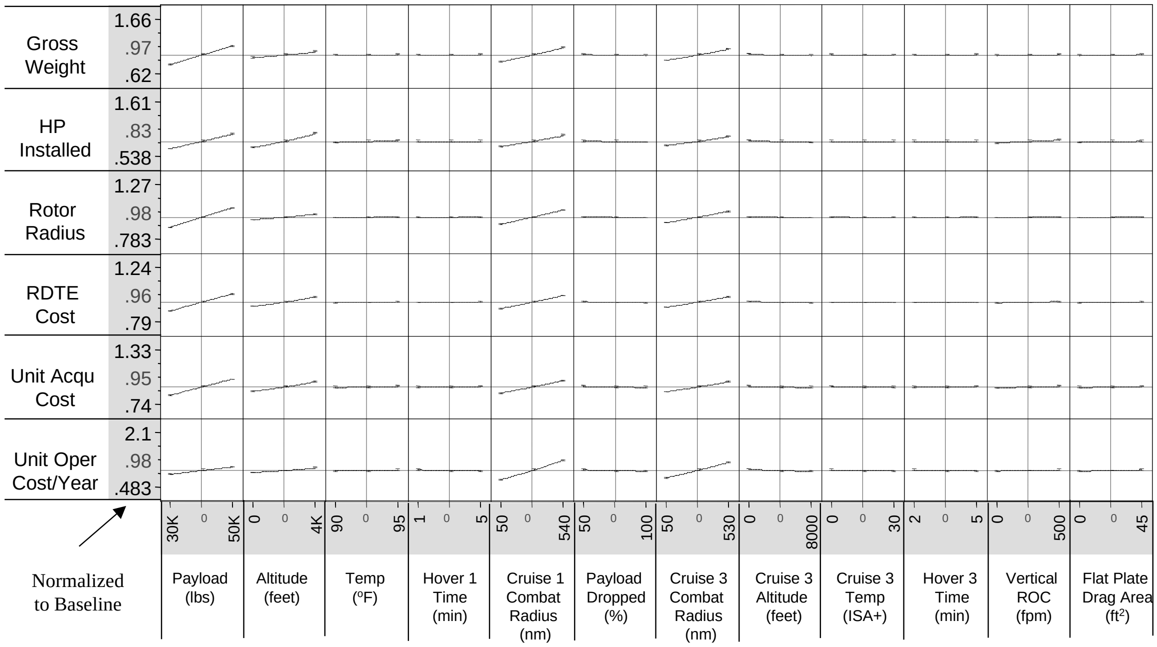

Figure 3: Mission Space Model

When the hairlines (red vertical lines) are moved to indicate the changing of a mission requirement value, the responses are automatically updated through the RSE. Thus, one can investigate the mission space by manipulation of the design variables to determine if an objective can be met. The slopes indicate the relative effect each variable has on the objectives. On a more practical note, this screen is often helpful as a debugging tool since trends can be verified and potential mistakes located.

An interesting probabilistic application of the Mission Space Model entails the bounding of the mission space. At this point, the Mission Space Model is built around a user-defined baseline vehicle with the input variables being mission requirements. Assumptions are made about vehicle attributes such as disk loading, blade loading, rotor tip speed, etc. Likewise, technology assumptions are made concerning technology metrics such as engine specific fuel consumption, vehicle component weight and vehicle aerodynamic performance. These assumptions are part of the initial vehicle configuration, i.e. the baseline vehicle. The effect of these assumptions needs to be tested under the uncertainties associated with mission requirements. This is accomplished by bounding the problem using the Mission Space Model. A uniform distribution is placed on each mission parameter with the limits of this distribution set by the range used in the DOE to create the MSM. This formulation ensures that each value within the range is equally likely and running a Monte Carlo Simulation of appropriate size (say 10,000 cases) will sufficiently represent the uncertainty of each mission parameter. In this way, the resulting distributions for the responses reflect the best and worst case mission profile and represent a bounding of the values possible for each response. Each of the 10,000 case runs represent a new baseline vehicle and together they represent a family of vehicles with the same assumptions governing vehicle attributes and technology level. The resulting cumulative distribution for gross weight is shown in Figure 4

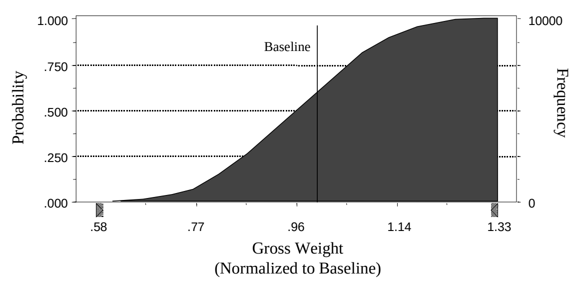

Figure 4: Bounding the Problem: Gross Weight

The gross weight values are normalized (by the baseline value) and indicate the bounding gross weights lie between 58% and 133% of the original baseline value. This large interval is due to the large range in payload and combat radius considered in this MSM. A line indicating the original baseline vehicle gross weight shows that there is a 60% probability of finding a vehicle in this family that weighs less than or equal to the original baseline. Conversely, if the designer specifies an 80% probability of success as the threshold, then the vehicle weighs less than or equal to 109% of the original baseline value.

Figure 5 shows the cumulative distributions for four other responses. Suppose the designer has some information about the engine used for this FTR which indicates the maximum installed horsepower obtainable if three engines are used. If this target is slightly higher than the baseline value, then this figure shows there is a 90% probability that a mission requires less installed horsepower. To ensure satisfactory installed power for the most stringent mission, the designer must look for an engine that has 120% of the baseline installed power. This result could assist the designer in determining if new engines or engine technologies must be sought. The empty weight distribution indicates a 75% probability of success of finding a vehicle whose empty weight is at or below the baseline value. If a limit is placed on empty weight at 114% of the baseline (perhaps for compatibility with shipboard use) then there is little worry an aircraft meets this constraint. If the limit is closer to the baseline value, however, then the designer needs to investigate technologies for reducing structural weight as well as SFC. In a similar manner, the Unit Acquisition Cost distribution is used to determine if technologies are needed to reduce recurring or non-recurring production cost including manufacturing processes. Finally, the distribution for blade aspect ratio indicates the need to reconsider vehicle attribute assumptions if blade aspect ratio is limited to a value near the baseline. Changes in blade loading, disk loading, rotor-tip speed, number of main rotor blades as well as rotor aerodynamic efficiency could facilitate the meeting of this constraint.

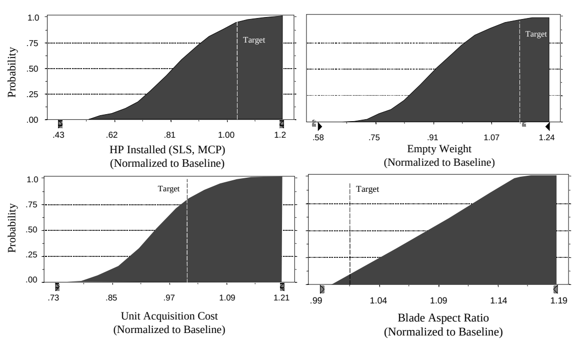

Figure 5: Bounding the Problem: Four Responses

UNIFIED TRADEOFF ENVIRONMENT

The previous section established the feasibility of creating a Mission Space and demonstrated its use in a probabilistic design problem. This section concentrates on the construction and application of a Unified Tradeoff Environment (UTE) containing five mission requirements, five vehicle attributes, and nineteen technology dials. The UTE is constructed using a single integrated Design of Experiments and is built around the helicopter variant of the Future Transport Rotorcraft.

The five mission parameters used to build the Unified Tradeoff Environment are shown in Table 5 and represent the major factors influencing the synthesis and sizing of a Future Transport Rotorcraft. These mission parameters correspond to the master mission structure shown in Figure 2, and the following assumptions are made. The entire mission is flown at one temperature and altitude within the ranges shown in Table 5. This eliminates the Cruise 3 segment flying at best altitude but this requirement is less severe than flying at lower altitudes. The combat radius for Cruise 1 and 3 are flown in equal lengths and cannot be controlled individually. This should not present a problem since most missions include an inbound and outbound cruise of equal lengths. The payload is assumed to be internal which would be consistent with a vehicle or troop carrying assault mission with an initial hover. Finally, the payload dropped is set at 50% since it is the worst case scenario.

Table 5: Mission Requirements for Building UTE

Mission Parameter	Units	Minimum	Maximum
Payload	lbs	30000	50000
Combat Radius	nm	150	540
Vertical ROC	fpm	0	500
Ambient Temp	deg F	60	95
Ambient Altitude	feet	0	4000

The vehicle attributes chosen for this Unified Tradeoff Environment are shown in Table 6 with their applied ranges. For proprietary reasons, the ranges are shown as a percent increase or decrease from the baseline values. The fuselage wetted area and the flat plate drag area allow the user to apply fuselage size changes as well as improvements associated with the infusion of technology advancements or drag reduction strategies.

Table 6: Vehicle Attributes for Building UTE

		Variable Ranges	
Vehicle Attribute	Units	Minimum (% Baseline)	Maximum (% Baseline)
Blade Loading	nd	0	+20
Disk Loading	lbs/ sq ft	-5	+20
Fuselage Wetted Area	sq feet	-10	+20
Flat Plate Drag Area	sq feet	-15	+45
Tip Speed	fpm	-5	+10

The technology metrics or dials chosen for this UTE are presented in Table 7 and allow the mapping of specific technologies. These technology dials allow the user to assess the impact of technology assumptions made when sizing the baseline vehicle as well as the application of more advanced technologies (updating baseline technology assumptions where appropriate).

Table 7: Technology Dials for Building UTE

	Variable Ranges	
Technology Metric Dial	Minimum (% Original)	Maximum (% Original)
Blade Weight	-25	+10
Hub Weight	-25	+5
Fuselage Weight	-25	-5
Engine Weight	-40	-10
Drive System Weight	-35	-10
Rotor Controls Weight	-10	+10
Specific Fuel Consumption	-45	-20
Vertical Drag	-15	+5
FoM Incr/Decr	0	+5
Fuselage Production Cost	-40	+5
Transmission Prod Cost	-25	+5
FCS Production Cost	-20	+10
Rotor Production Cost	-20	+10
Engine Production Cost	-35	+10
Engine Maintenance Cost	-35	+20
Airframe $/FH	-30	+10
Dynamics MTBF	-10	+20
Dynamics $/FH	-30	+10
Engine $/FH	-35	+10

The specific technologies chosen for this UTE are shown in Table 8. The mapping of each technology to a vector of technology dials is also shown and illustrates the benefits and penalties associated with infusing these technologies. The column labeled "Baseline" reflects the original technology assumptions in creating the baseline vehicle. When technologies are applied to the vehicle, the benefits or penalties derived from that technology are used to update the original assumptions. Thus if the Advanced Engine is applied, then specific fuel consumption is reduced by an additional five percent. These technologies are compatible (i.e. they can be placed on the aircraft together), therefore, there are 16 technology combinations possible. When applying technology combinations, it is assumed that the vectors mapping the technologies to technology dials are additive.

Table 8: Mapping Four Technologies

	Percent Change from Original Metric Value				
	T1	T2	T3	T4	
Technology Metric Dial	Advanced Fuselage	Advanced Transmission	Advanced Engine	Variable Geometry Rotor	Baseline
Blade Weight				+3	-10
Hub Weight				+5	-10
Fuselage Weight	-25	+3			-10
Engine Weight			-55		-10
Drive System Weight		-17			-13
Rotor Controls Weight				+5	
Specific Fuel Consumption			-40		-35
Vertical Drag	-3	+3		-5	
FoM Incr/Decr				+5	
Fuselage Production Cost	-15				
Transmission Prod Cost		-25			
FCS Production Cost				+5	
Rotor Production Cost				+10	
Engine Production Cost			-35		
Engine Maintenance Cost	+3	+3	-35		
Airframe $/FH	+4				
Dynamics MTBF				-5	
Dynamics $/FH				+5	
Engine $/FH			+4		
Flat Plate Drag Area	-3			-10	

The Unified Tradeoff Environment built for this study consists of 29 input variables while ten system-level responses are tracked. A custom Design of Experiments (DOE) is generated for 29 variables requiring 1024 cases. After completing these cases in accordance with the DOE and collecting the response data for each run, the response surface equations are built. A statistical check (R^2) for model fit indicates the RSEs provide an excellent fit to the observed response data. The RSEs are checked for model completeness to verify the normality assumption for empirical model error. Finally, the predictive validation is conducted by comparing RSE results for the ten responses to actual analysis code results for 500 random cases. The percent difference between actual and predicted response values is tracked to determine RSE predictive capability. Table 9 shows the results of this confirmation test and indicates good overall predictions from this Unified Tradeoff Environment.

Table 9: UTE Model Validation Results

		Percent Difference Actual to Predicted		
Response	Model Fit (R Square)	Mean	Std Dev	Max
Gross Weight	0.9973	1.7	1.3	7.2
Empty Weight	0.994	2.0	1.6	8.5
Fuel Weight	0.995	5.6	5.2	25.0
HP Installed (SLS, MCP)	0.994	2.4	1.8	10.2
Rotor Radius	0.998	0.6	0.4	2.3
Blade AR	0.997	0.2	0.1	0.7
RDTE Cost	0.996	0.8	0.6	2.9
Unit Acquisition Cost	0.995	1.3	0.9	4.8
Unit Operating Cost / Year	0.997	3.5	2.8	14.7
LCC	0.996	1.7	1.3	6.7

Similar to the Mission Space Model study, the UTE is used in a probabilistic setting, which bounds the combined design space. In this study, uniform distributions are placed on disk loading, blade loading and tip speed in addition to the mission requirements. Thus a family of aircraft with different configurations and sized for various missions is generated. In addition to the baseline vehicle, this analysis is conducted by placing two different technology sets on the baseline aircraft. Technology Set 1 consists of the Advanced Fuselage, the Advanced Transmission and the Advanced Engine. Technology Set 2 consists of the Advanced Fuselage, the Advanced Engine and the Advanced Rotor. The resulting distributions for each response are overlaid on the same plot for investigation. Figure 6 shows the three distributions for gross weight. The baselines with technology sets applied obviously guarantee a sized vehicle with a gross weight less than the original baseline under mission and vehicle attribute uncertainty. Technology Set 2 is slightly better than Technology Set 1 in terms of gross weight. Setting the Probability of Success (POS) threshold at 75 percent, the two technology sets promise a vehicle that is 12 percent lighter than the baseline.

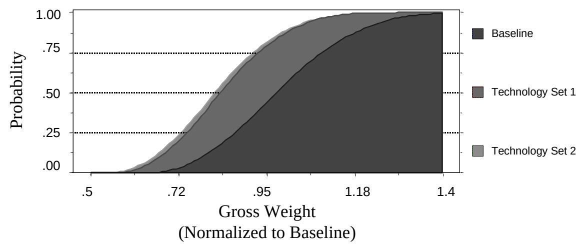

Figure 6: Gross Weight Distributions for Three Technology Levels

However, Figure 7 shows the three distributions for Acquisition Cost where there is more of a discrepancy between technology sets. Technology Set 2 provides the best results with respect to gross weight, however, the price is paid in Acquisition Cost. The difference between Technology Set 1 and 2 is the swapping of the Advanced Transmission and the Advanced Rotor. Obviously, the Advanced Rotor provides slightly better performance attributes but this is counter balanced by the increase in Acquisition Cost. This increased Acquisition Cost is the result of economic penalties placed on the flight control system and rotor system production costs when applying the Advanced Rotor. This figure indicates the maximum difference in Acquisition Cost occurs at an 85% POS and equates to a four percent difference. Thus, with the analysis and economic models available for this research and the assumptions made when mapping the Advanced Rotor, Technology Set 1 is the best choice.

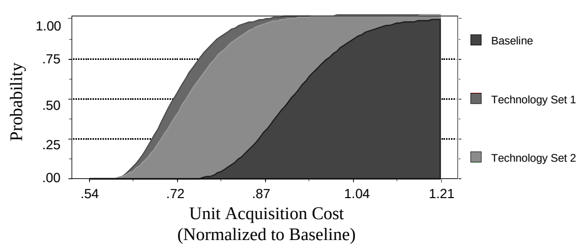

Figure 7: Unit Acquisition Cost Distributions for Three Technology Levels

Concluding Remarks

The research presented in this paper identifies mission requirements, vehicle attributes, technologies and design uncertainty as key elements in the decisions made in the early stages of design. It provides two probabilistic design environments that assist in making these decisions. The Mission Space Model deals with mission requirements and establishes the feasibility of creating an appropriate environment that captures a continuous mission space. The notion of a master mission structure is introduced to provide a reference point for the MSM changes and assistance in capturing multiple missions. The Unified Tradeoff Environment integrates the influence of mission requirements, vehicle attributes and technologies in one environment that is amenable to probabilistic techniques. Each environment is included in a probabilistic design exercise. The MSM is useful in identifying system constraints based on mission requirement uncertainty as well as the need for technology infusion. The probabilistic study using the UTE indicates the best technology combination under vehicle attribute and mission requirement uncertainty. These environments provide an efficient analytical engine for assessing, both deterministically and probabilistically, the simultaneous impact of mission requirement, vehicle attribute and technology changes.

Acknowledgments

The work presented in this paper is supported partially under a grant for the Office of Naval Research (Contract No. N00014-02-1-0015) and partially under Task 01-B-04-1.2-A1 for the Rotorcraft Industry Technology Association. The authors would like to thank Mr. Andrew Keith of the Sikorsky Aircraft Corporation for his support and guidance.

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